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CONTAINERLESS RIPPLE TURBULENCE

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ABSTRACT

One of the longest standing unsolved problems in physics relates to the behavior of fluids that are driven far from equilibrium such as occurs when they become turbulent due to fast flow through a grid or tidal motions. In turbulent flows the distribution of vortex energy as a function of the inverse length scale [or wavenumber 'k']of motion is proportional to $1/k^{5/3}$ which is the celebrated law of Kolmogorov. Although this law gives a good description of the average motion, fluctuations around the average are huge. This stands in contrast with thermally activated motion where large fluctuations around thermal equilibrium are highly unfavorable. The problem of turbulence is the problem of understanding why large fluctuations are so prevalent which is also called the problem of "intermittency".

Turbulence is a remarkable problem in that its solution sits simultaneously at the forefront of physics, mathematics, engineering and computer science. A recent conference [March 2002] on "Statistical Hydrodynamics" organized by the Los Alamos Laboratory Center for Nonlinear Studies brought together researchers in all of these fields. Although turbulence is generally thought to be described by the Navier-Stokes Equations of fluid mechanics the solution as well as its existence has eluded researchers for over 100 years. In fact proof of the existence of such a solution qualifies for a 1M$ millennium prize.

As part of our NASA funded research we have proposed building a bridge between vortex turbulence and wave turbulence. The latter occurs when high amplitude waves of various wavelengths are allowed to mutually interact in a fluid. In particular we have proposed measuring the interaction of ripples [capillary waves] that run around on the surface of a fluid sphere suspended in a microgravity environment.

The problem of ripple turbulence poses similar mathematical challenges to the problem of vortex turbulence. The waves can have a high amplitude and a strong nonlinear interaction. Furthermore, the steady state distribution of energy again follows a Kolmogorov scaling law; in this case the ripple energy is distributed according to $1/k^{7/4}$. Again, in parallel with vortex turbulence ripple turbulence exhibits intermittency [Wright et al Science 278, 1609 (97)].

The problem of ripple turbulence presents an experimental opportunity to generate data in a controlled, benchmarked system. In particular the surface of a sphere is an ideal environment to study ripple turbulence. Waves run around the sphere and interact with each other, and the effect of walls is eliminated. In microgravity this state can be realized for over 2 decades of frequency.

Wave turbulence is a physically relevant problem in its own right. It has been studied on the surface of liquid hydrogen [Brazhnikov et al] and its application to Alfven waves in space is a source of debate.[P. Goldreich]. Of course, application of wave

turbulence perspectives to ocean waves has been a major success of V. E. Zakharov. [Kolmogorov Spectra of Turbulence, Springer, Berlin 1992].

The experiment which we plan to run in microgravity is conceptually straightforward. Ripples are excited on the surface of a spherical drop of fluid and then their amplitude is recorded with appropriate photography. A key challenge is posed by the need to stably position a 10cm diameter sphere of water in microgravity. Two methods are being developed. Orbitec is using controlled puffs of air from at least 6 independent directions to provided the positioning force. This approach has actually succeeded to position and stabilize a 4cm sphere during a KC 135 segment. Guigne International is using the radiation pressure of high frequency sound. These transducers have been organized into a device in the shape of a dodecahedron. This apparatus 'SPACE DRUMS' has already been approved for use for combustion synthesis experiments on the International Space Station.

A key opportunity presented by the ripple turbulence data is its use in driving the development of codes to simulate its properties. A head start on this aspect of the project is being developed at NASA Glenn Research Center.

SCIENCE REQUIREMENT

What are the differences in the way in which energy is distributed in turbulent flow and in thermal equilibrium ?

Thermal Equilibrium	**Turbulence**

Experimentally controlled parameter

T = temperature	q = energy throughput = ergs/cm^{2}sec

Probability distribution for wave motion

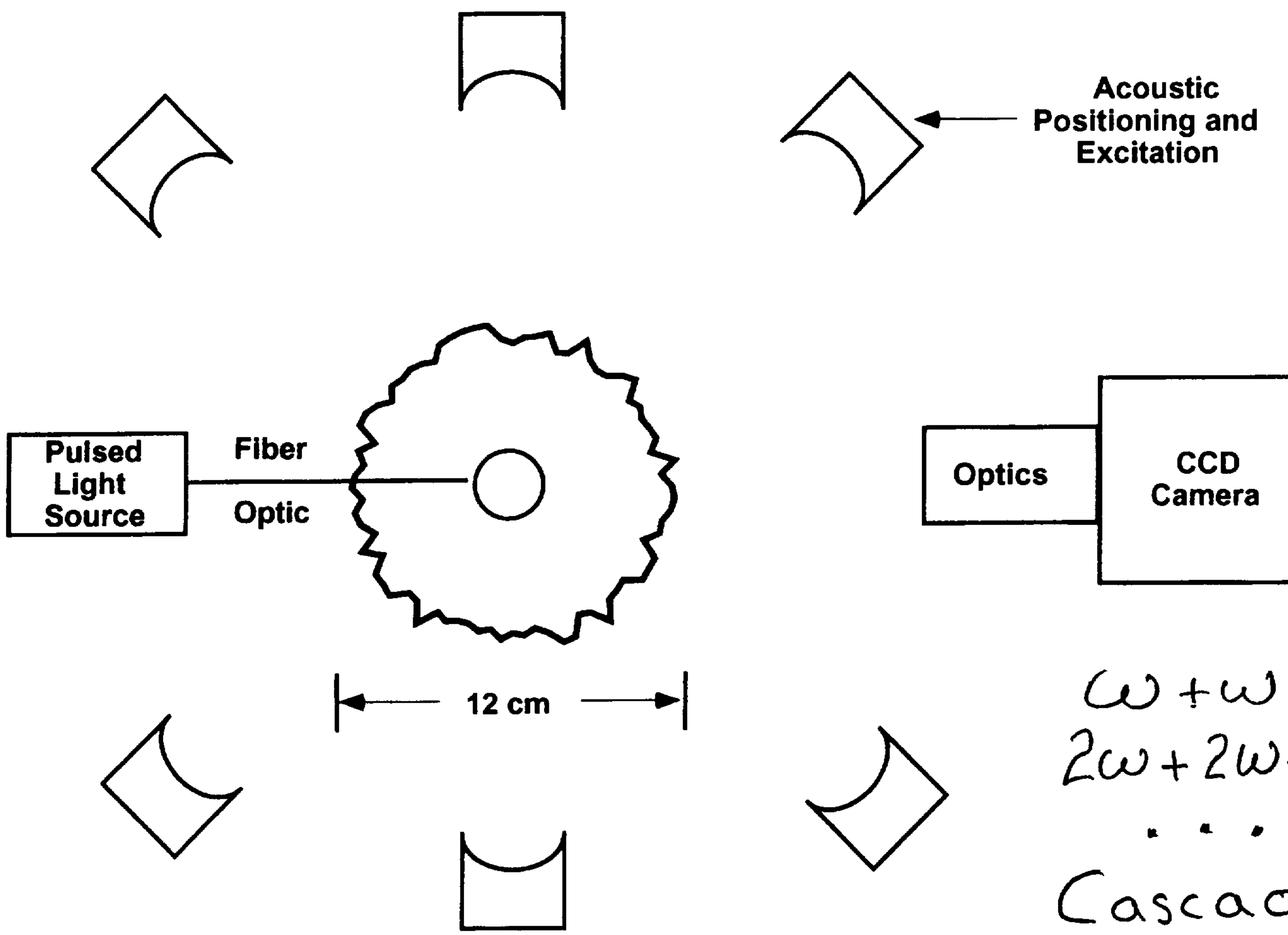
$$P(\{\varepsilon\}, T) \sim e^{-\Sigma(\varepsilon_i / k_B T)} \qquad P(\{\varepsilon\}, q) = ??$$

$$\varepsilon_i = \text{energy in mode i}$$

$$\langle \varepsilon_i \rangle = k_B T \qquad \langle \varepsilon_k \rangle \sim \frac{q^{1/2}(\rho\sigma)^{1/4}}{k^{11/4}}$$

"Equipartition"	"Kolmogorov cascade"
Gaussian	Intermittency
boring	interesting
	Competition between randomization and structure

Proposed Flight Experiment



$\omega + \omega \rightarrow 2\omega$

$2\omega + 2\omega \rightarrow 4\omega$

. . .

Cascade

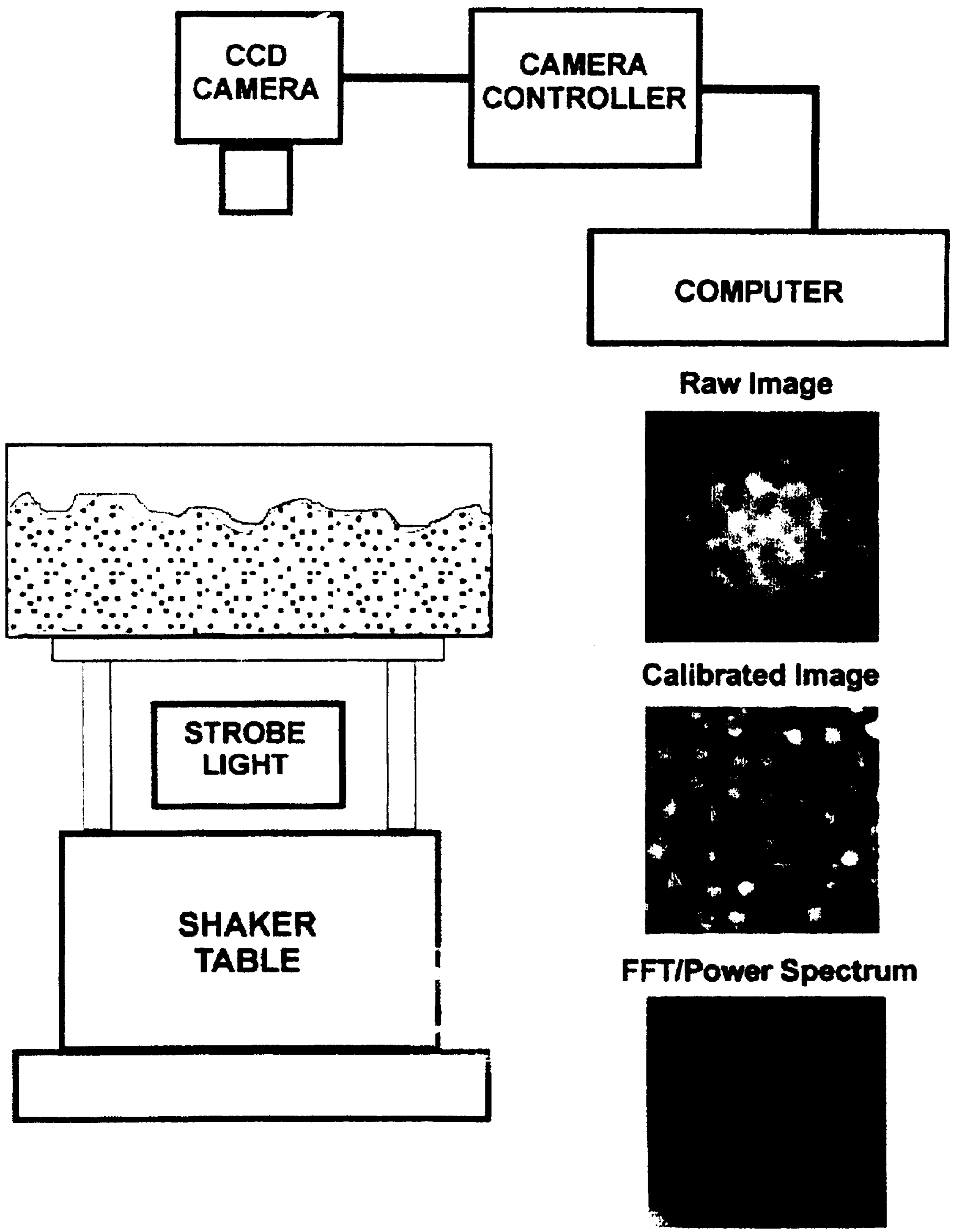
Big whorls have little whorls
Which feed on their velocity;
And little whorls have lesser whorls,
And so on to viscosity
(in the molecular sense) ... Richardson 1926

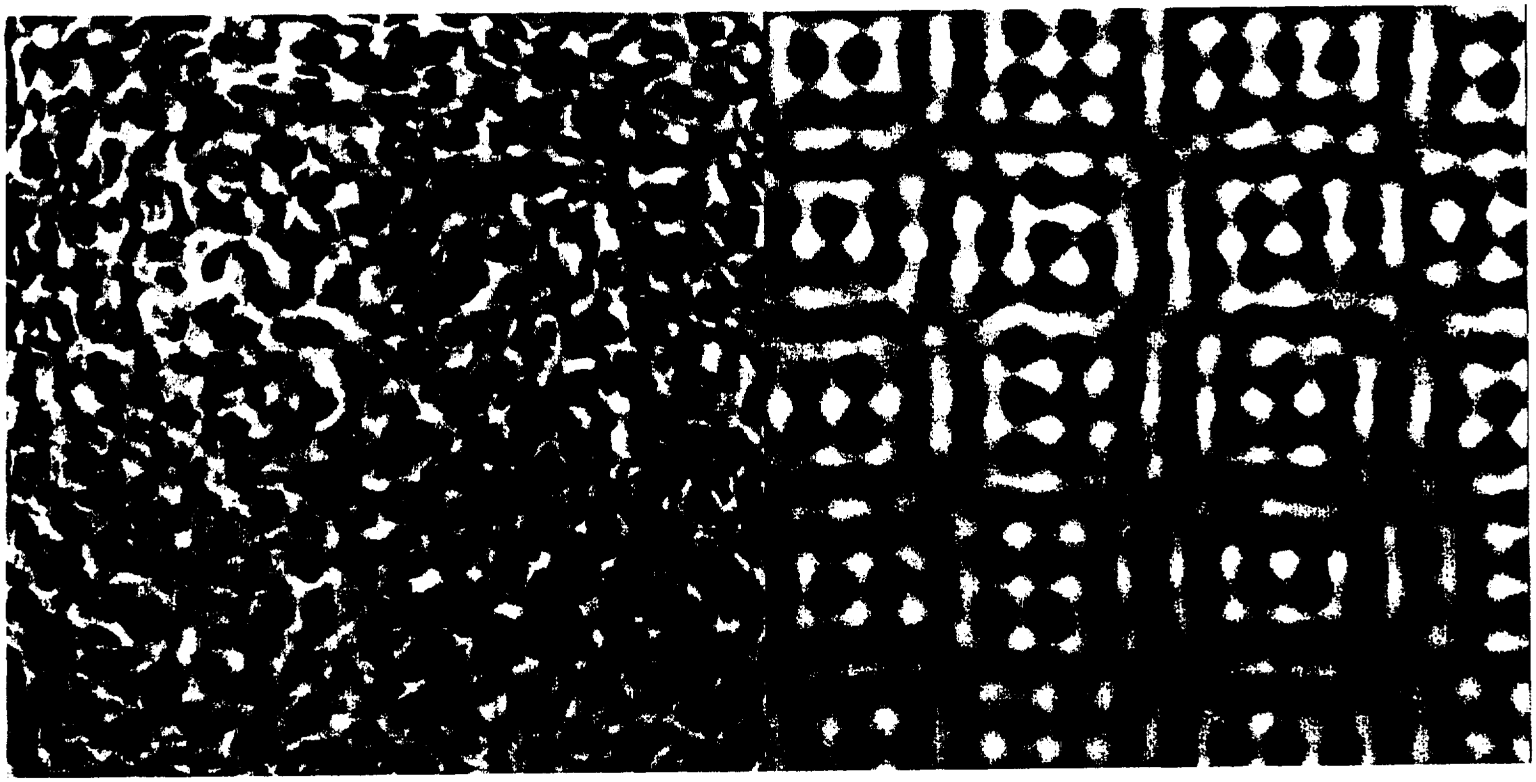
The wind comes in gusts ... attributed to Landau
1942 - Kazan

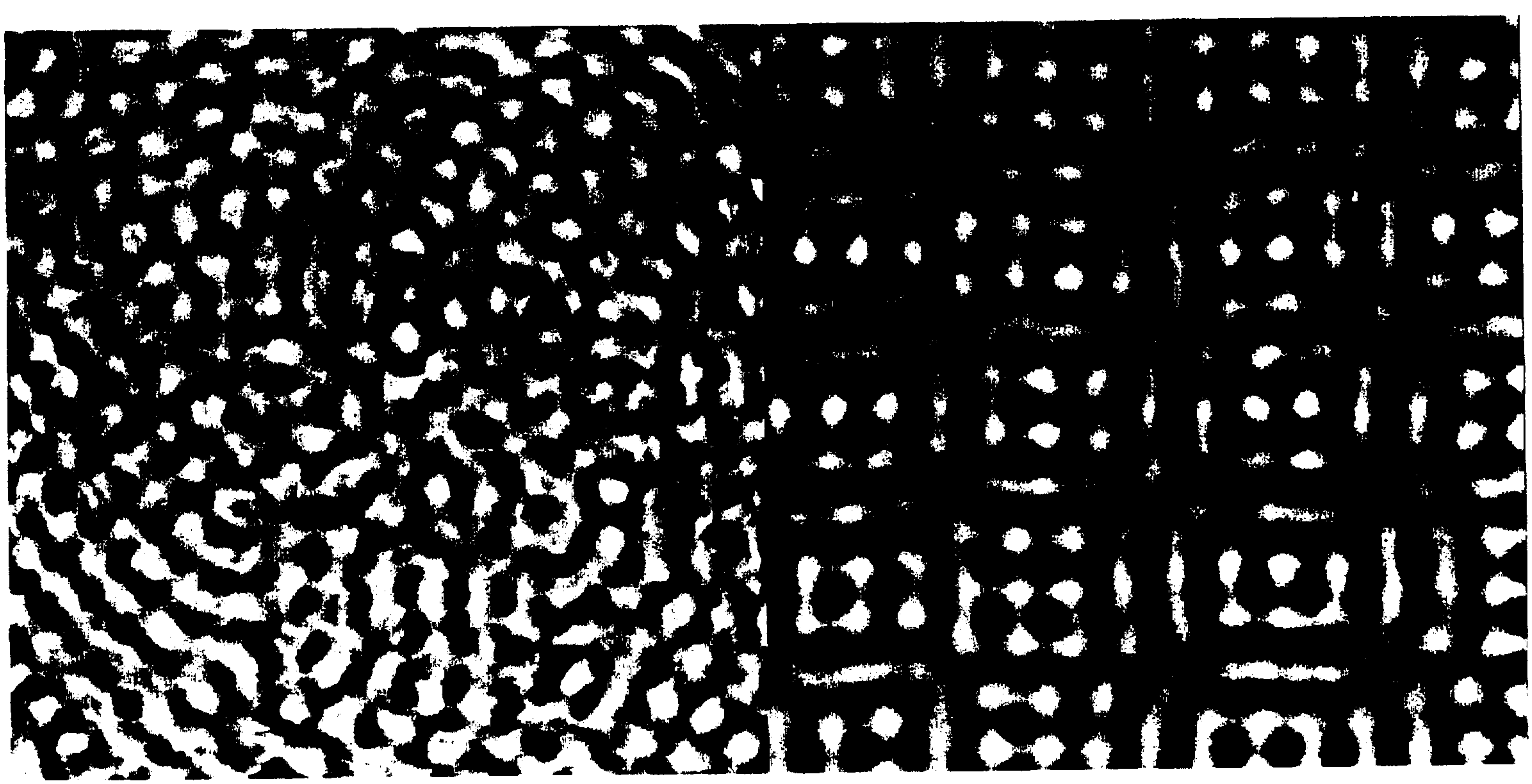
When I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics and the other is turbulent motion of fluids. And about the former I am really optimistic.

Sir Horace Lamb 1932

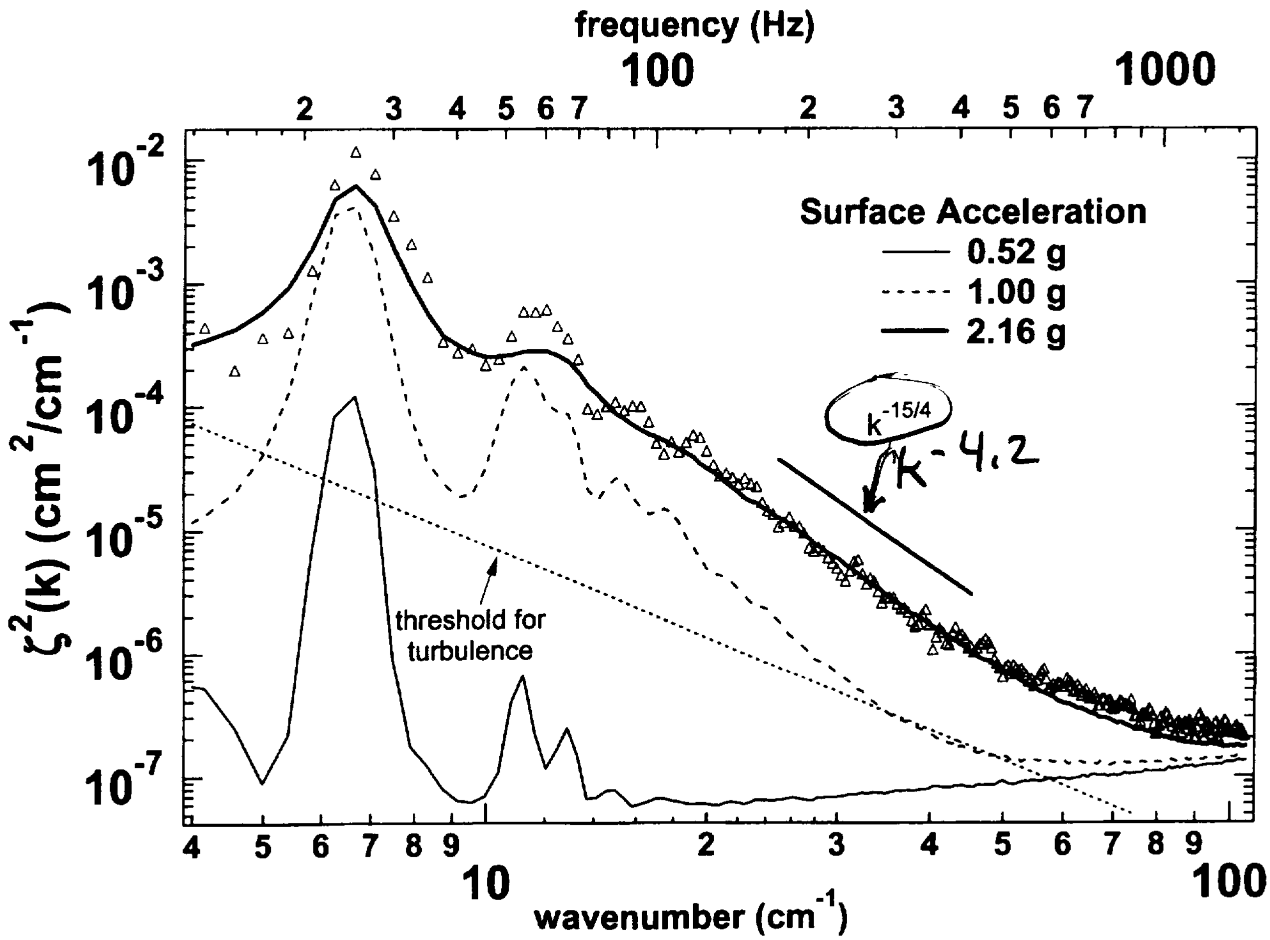
Excitation and Measurement of Ripples [Ground-based]







Power Spectrum of Ripple Turbulence



POWER SPECTRUM FOR RIPPLE TURBULENCE

$$\omega^2 = (\sigma/\rho)k^3$$

σ = surface tension

cascade from $k \rightarrow 2k$ =

$$\left.\frac{\partial E_k}{\partial t}\right]_+ = \omega_k G^2 E_k \frac{E_k}{\sigma} - 4\mu k^2 E_k$$

$E_k \cong \sigma k^2 \zeta_k^2$ = ripple energy between k and 2k

μ = kinematic viscosity ~ .01 cm2/s for water,
$G^2 = 8\pi^4/13$ = nonlinear coefficient

$$\left.\frac{\partial E_k}{\partial t}\right]_+ = q = \frac{\text{ergs}}{\text{cm}^2\text{s}} = \text{energy throughput}$$

in the steady state, $E_k \sim \left[q\sigma/g^2\omega_k\right]^{1/2}$.

therefore spectral density

$$e(\omega) \sim 1/\omega^{3/2}$$

$$\zeta^2(\omega) \simeq \frac{\sigma^{1/6}q^{1/2}/\rho^{2/3}}{\omega^{17/6}}; \; \zeta^2(k) \simeq \frac{q^{1/2}\rho^{1/4}/\sigma^{3/4}}{k^{15/4}}$$

$$\langle\zeta^2(r)\rangle = \langle\zeta^2(t)\rangle = \int \zeta^2(k)dk = \int \zeta^2(\omega)d\omega$$

OPERATIONAL DEFINITION OF TURBULENCE

$$\left(\frac{\partial E_k}{\partial t}\right)_+ = G^2 \omega_k E_k \frac{E_k}{\sigma} - 4\mu k^2 E_k$$

1) Interaction rate due to nonlinear scattering:

$$\frac{1}{\tau_{NL}} \equiv \frac{1}{\tau_+} \equiv G^2 \omega_k \frac{E_k}{\sigma} \gg 4\mu k^2$$

$$\text{or } M^2 > 1/G^2 Q,$$

where M is the Mach number and Q is the quality factor.

2) There must be many modes in the bandwidth determined by τ_+:

$$n(\omega)/\tau_+ \gg 1$$

where n is the density of modes

$$n(\omega) \approx \frac{S\omega^{1/3}}{3\pi\left(\sigma/\rho\right)^{2/3}}$$

and S is the surface area. $S \approx 10 \times 10\ cm^2$, $\frac{\omega}{2\pi} \approx 100$ Hz

$n \sim 5$ seconds

Turbulence, not Chaos !

$M^2 \sim .1$, $G \sim 5.$

$n/\tau_+ \sim 10^4$

STOSSZAHL-ANSATZ

$$<I_i> = \int I_i P dI d\theta$$

Kinetic Equation for Waves:

$$d<I_i>/dt \sim \varepsilon^2 c^2 \sum \delta(\omega_{ijk}) <I_j I_k>$$

To close the equation requires a stosszahl ansatz -or equivalent:

$$<I_{ii} I_{jj}> = <I_{ii}><I_{jj}>$$

RENORMALIZED WAVE VELOCITY:

$$\dot{\theta}_i = \omega_i + \int \dot{\phi}(I) dI P d\theta = \omega_i + \int \dot{\phi}(I) P dI d\theta$$

where $\phi = \theta - \omega t$

$$P_1 \simeq i\pi\epsilon \sum_{ijk} \delta^{-}(\omega_{ijk}) c I^{3/2} e^{i\theta} \nabla \bar{P}$$

$$\frac{d}{dt}\left[<I_p I_q> - <I_p><I_q>\right] \sim \epsilon^2 N C_{jk,8}$$

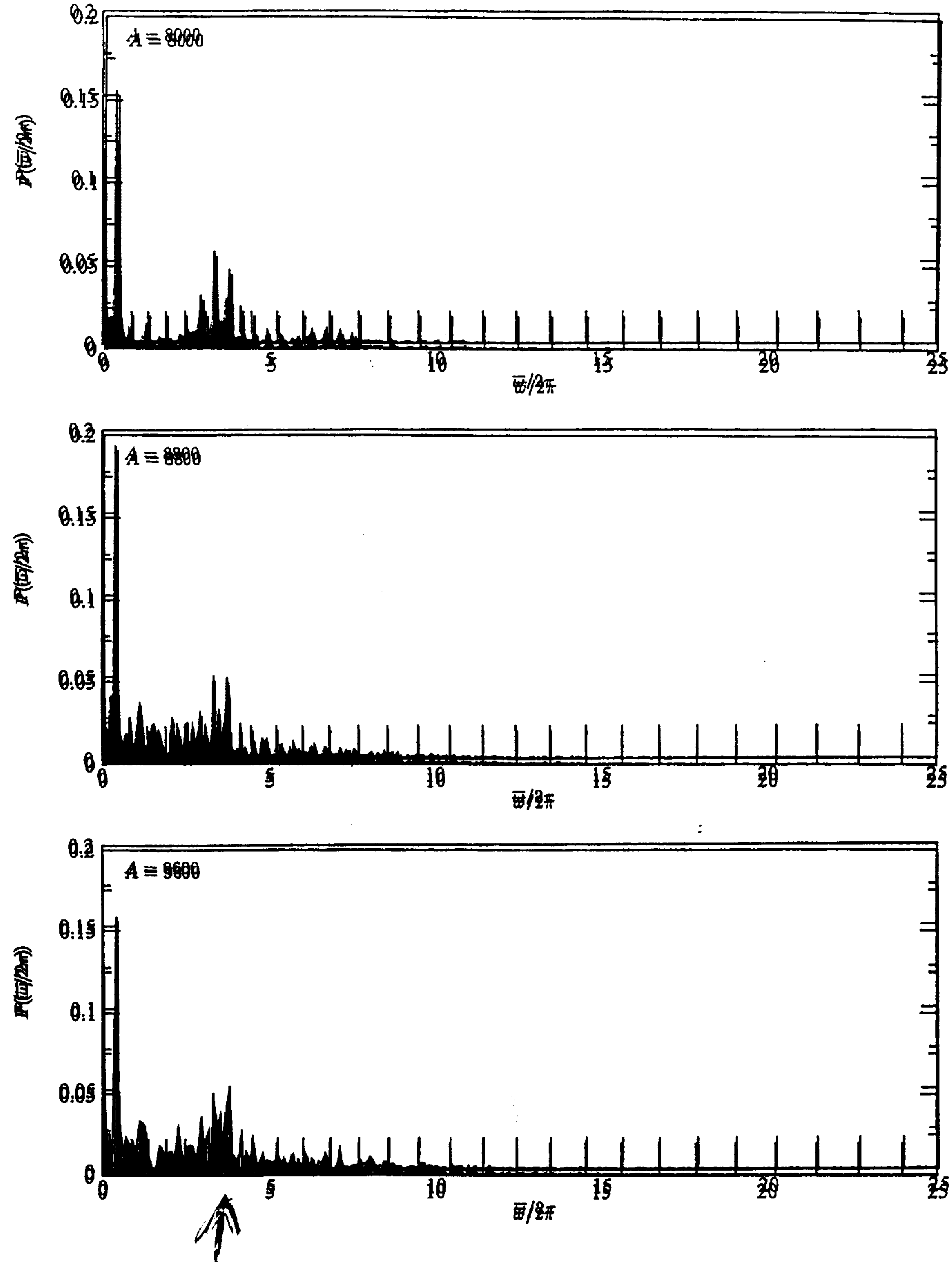
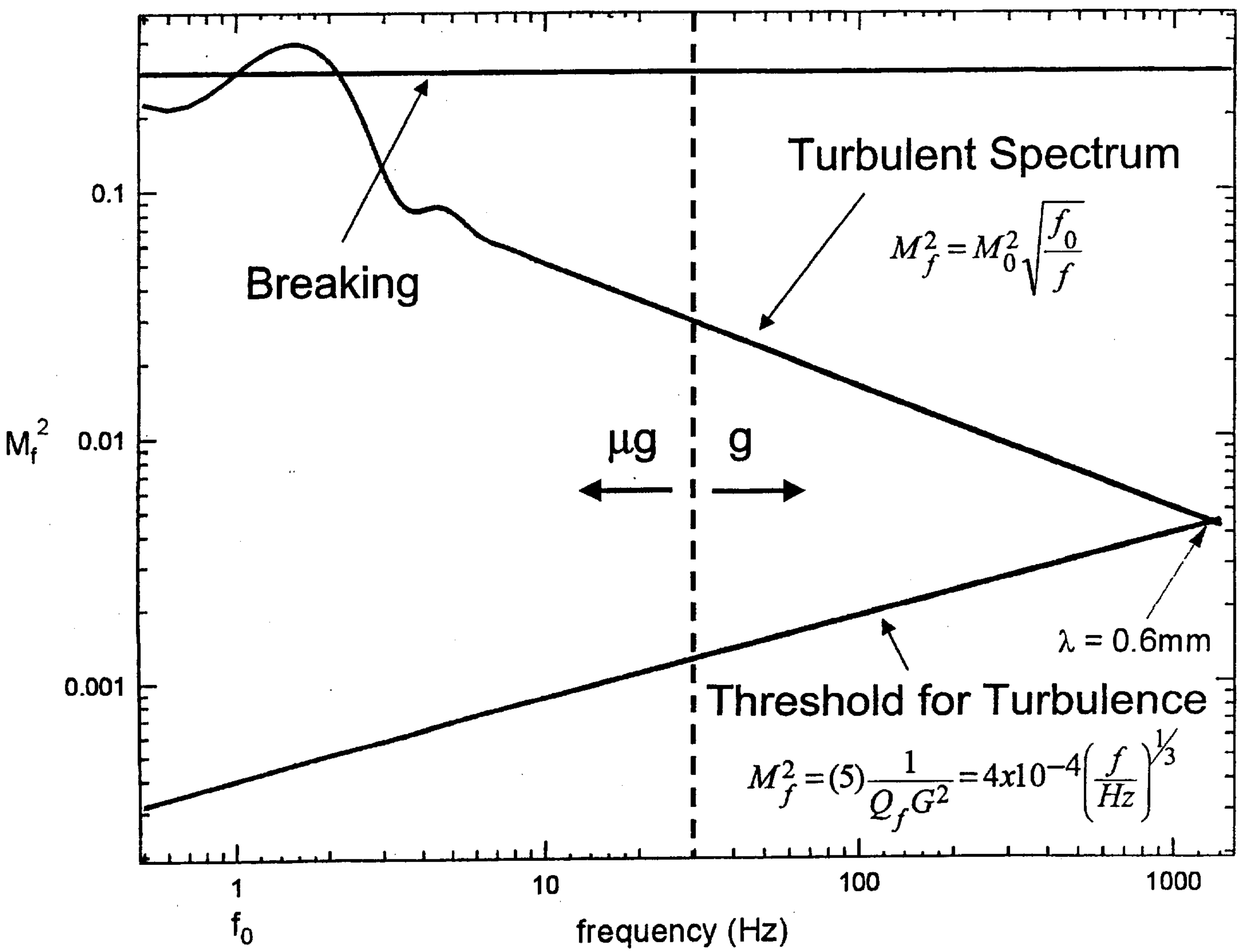
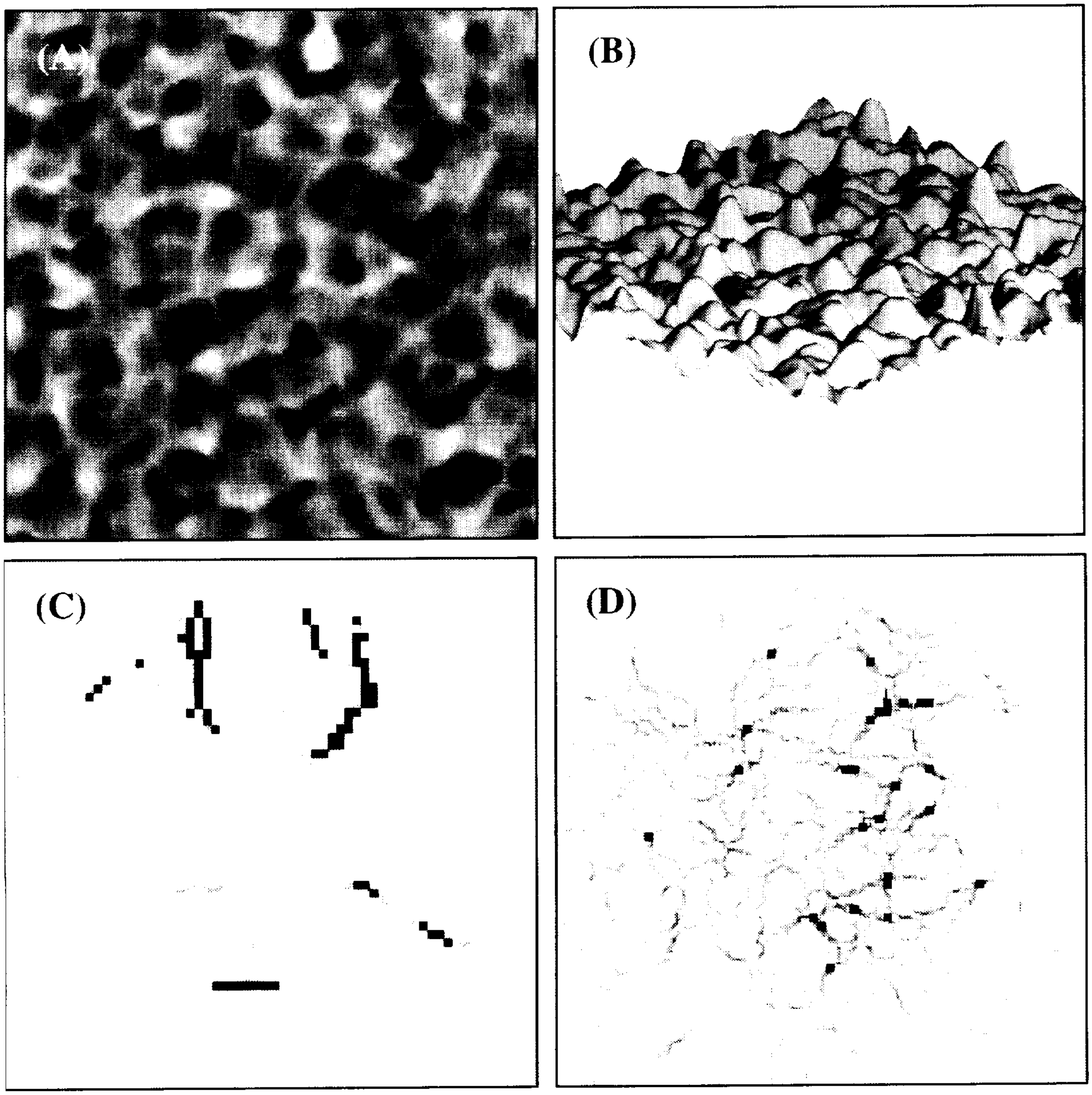


FIGURE 4. Power spectrum versus dimensionless frequency $\bar{\varpi}/2\pi$ for the data shown in figure 2. The vertical lines along the frequency axis are the natural frequencies $\bar{\varpi}_{l0}/(2\pi)$ for each of the symmetric spherical harmonics $l = 2, \ldots, 80$.


Turbulent Spectrum
$M_f^2 = M_0^2 \sqrt{\frac{f_0}{f}}$
Breaking
μg
g
λ = 0.6mm
Threshold for Turbulence
$M_f^2 = (5)\frac{1}{Q_f G^2} = 4x10^{-4}\left(\frac{f}{Hz}\right)^{1/3}$
$M_f^{\ 2}$
0.1
0.01
0.001
1
10
100
1000
f_0
frequency (Hz)

Fluctuations Around Kolmogorov Spectrum are Large

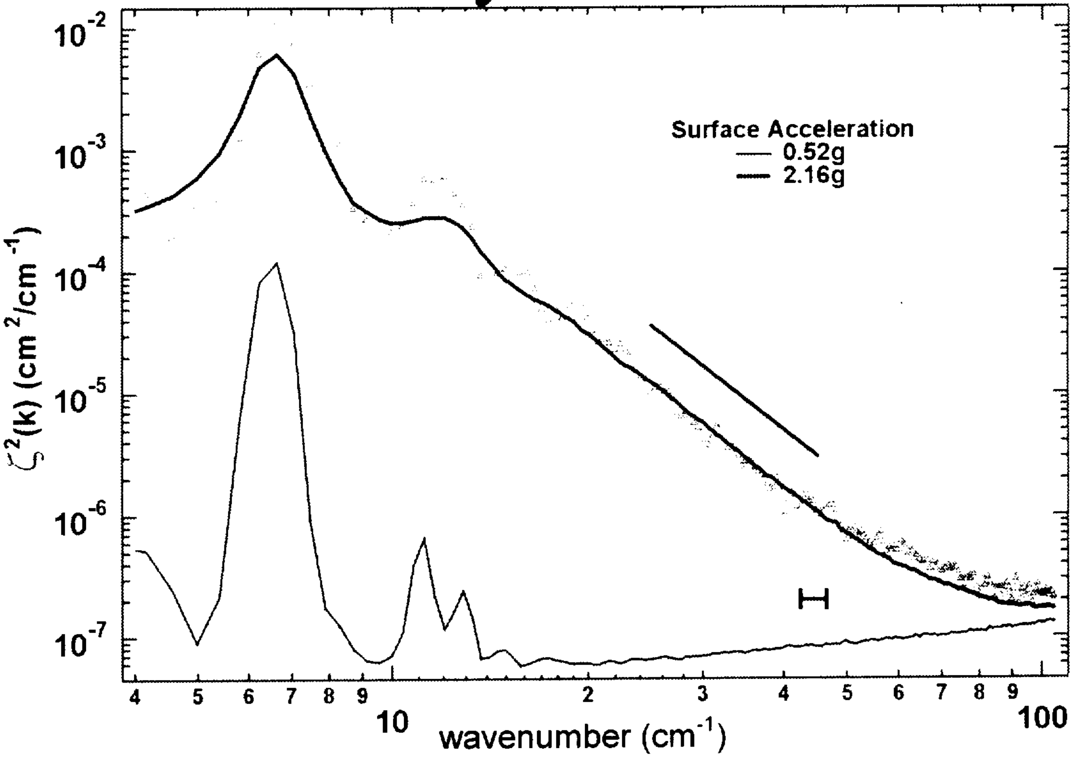


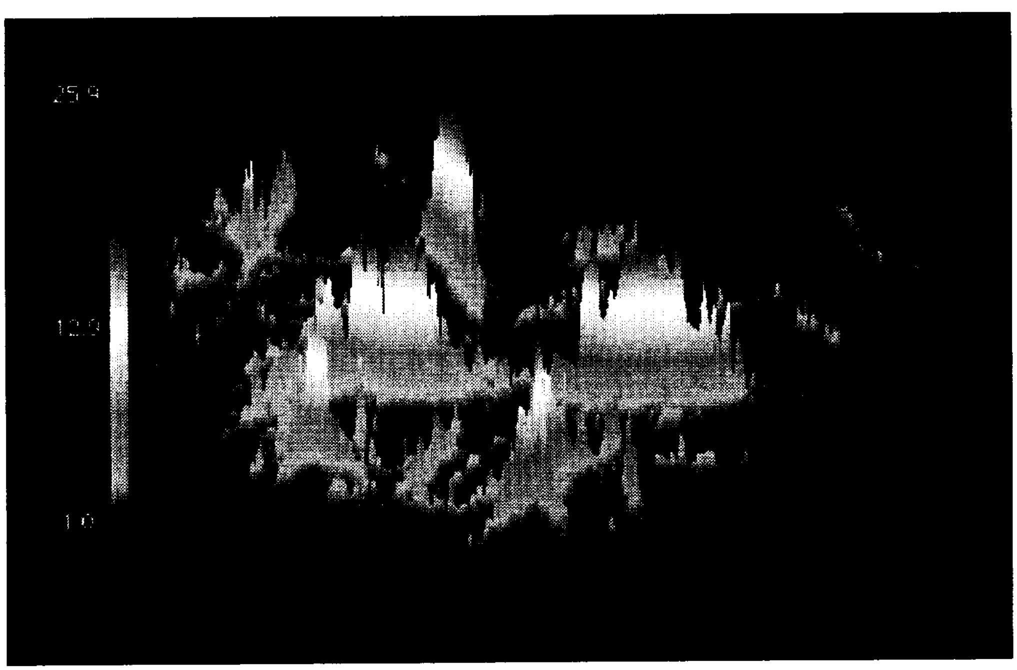
Kolmogorov Spectrum Measured Phases

Randomized Phases

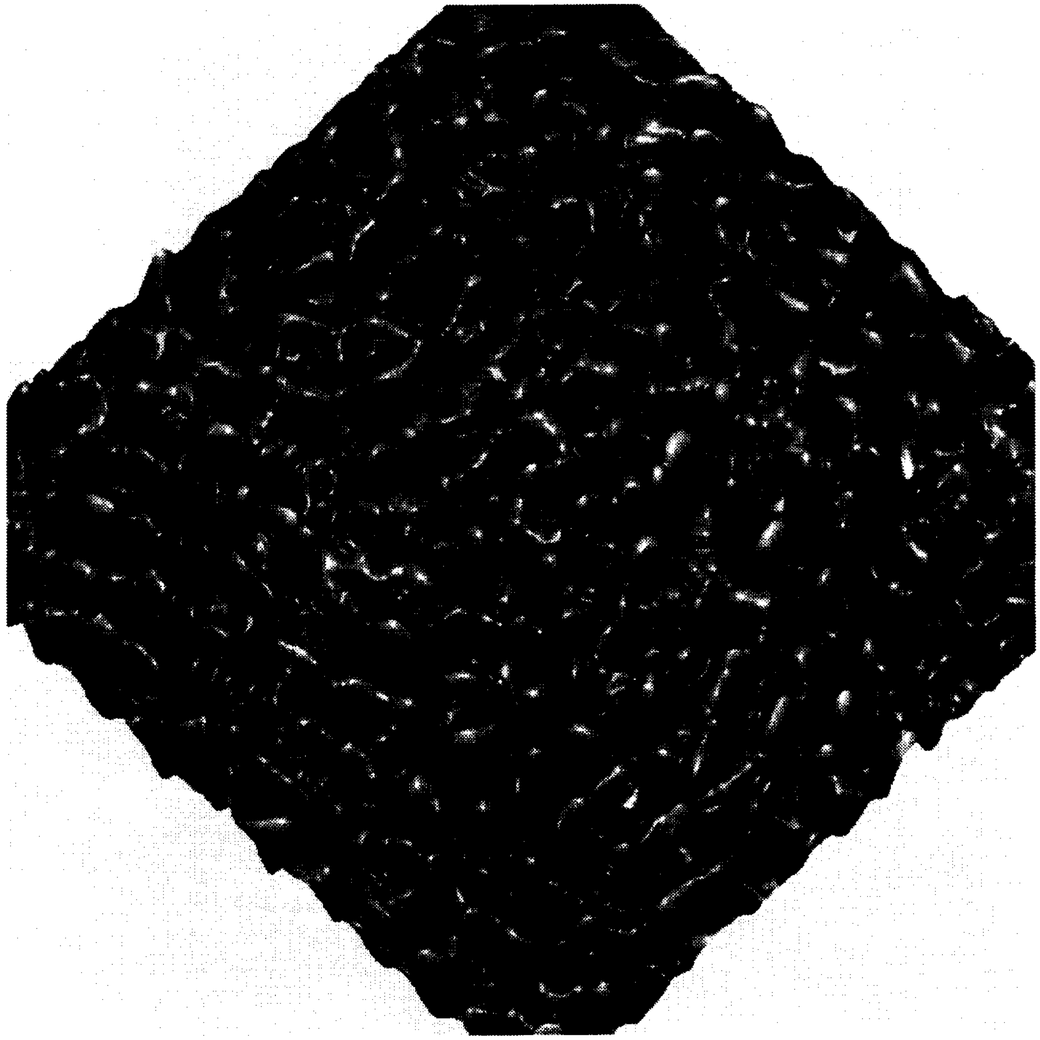
$\left(\lambda_0 \nabla^2 \zeta\right)^2 > 5$ rms for 16 pixels are indicated by blackening those regions

Intermittency in Turbulence

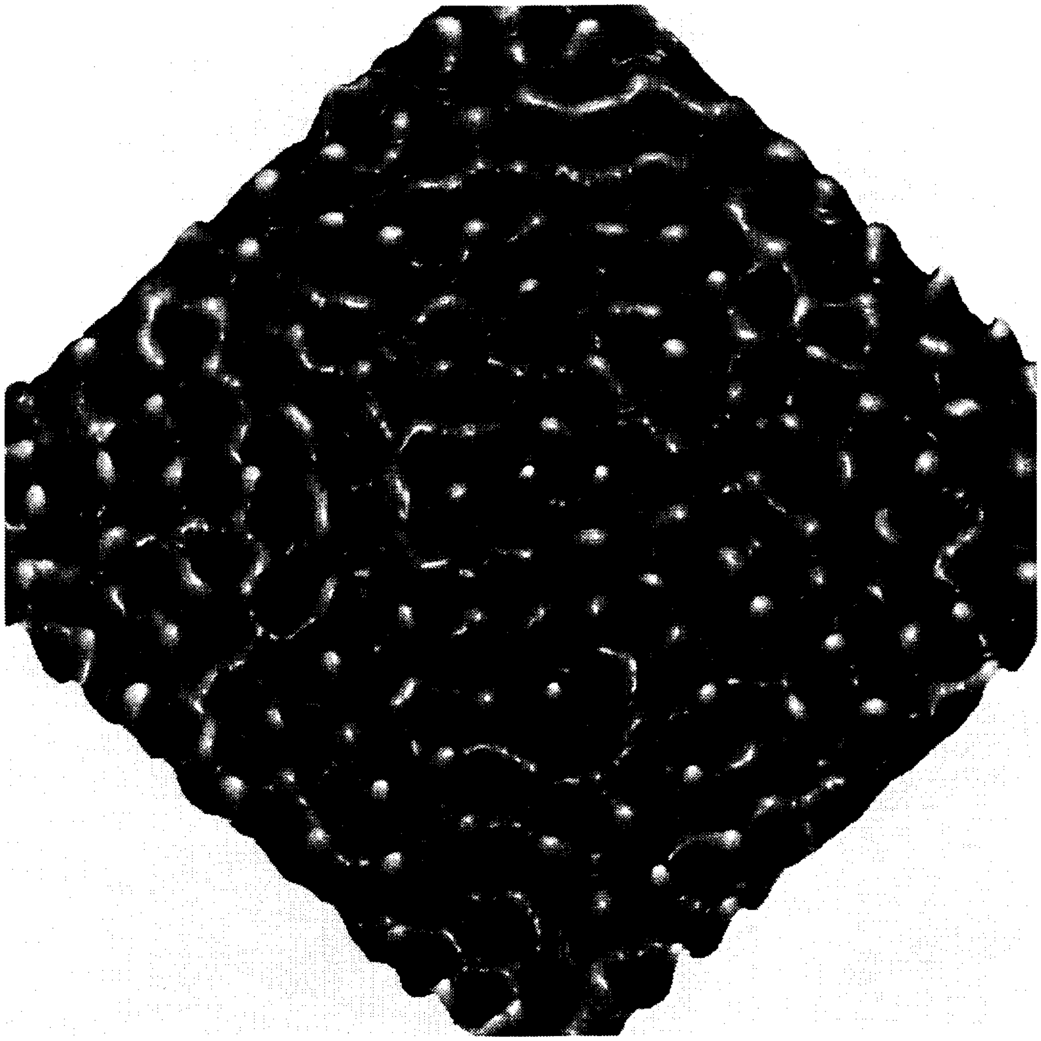




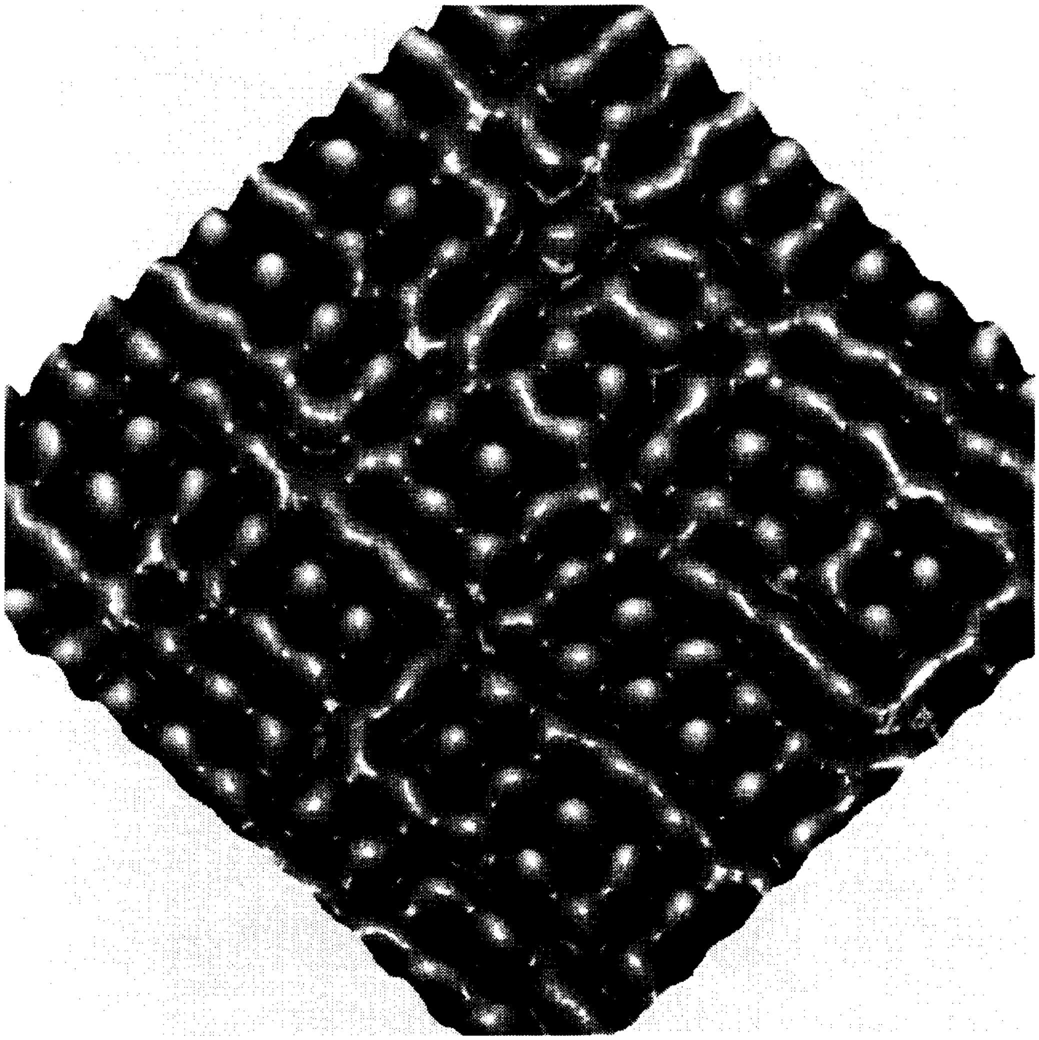
Plot of $\left(\lambda_0 \nabla^2 \zeta\right)^2 \propto$ local dissipation



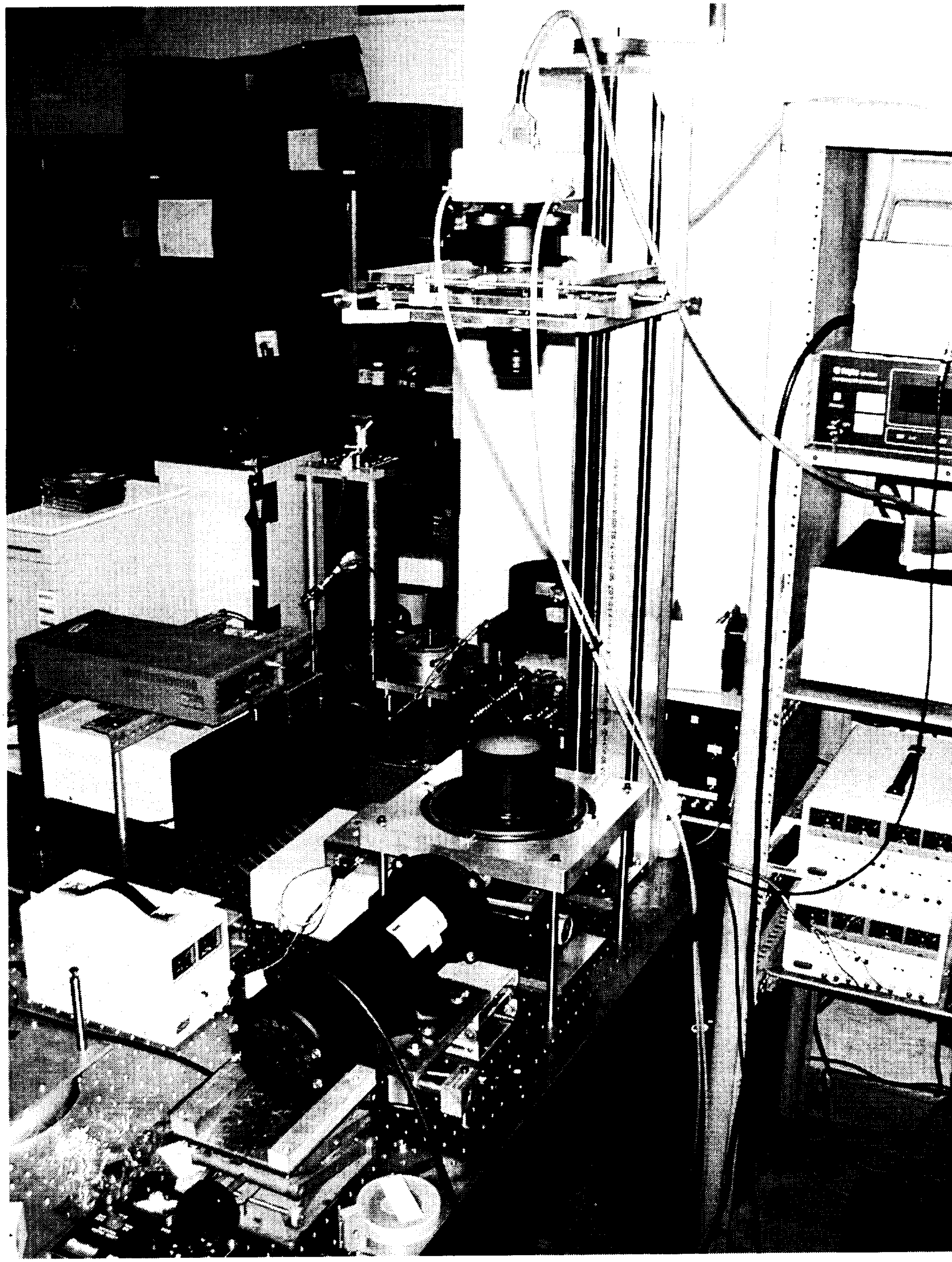
RippleHighAmpl



RippleMedAmpl



RippleLowAmpl



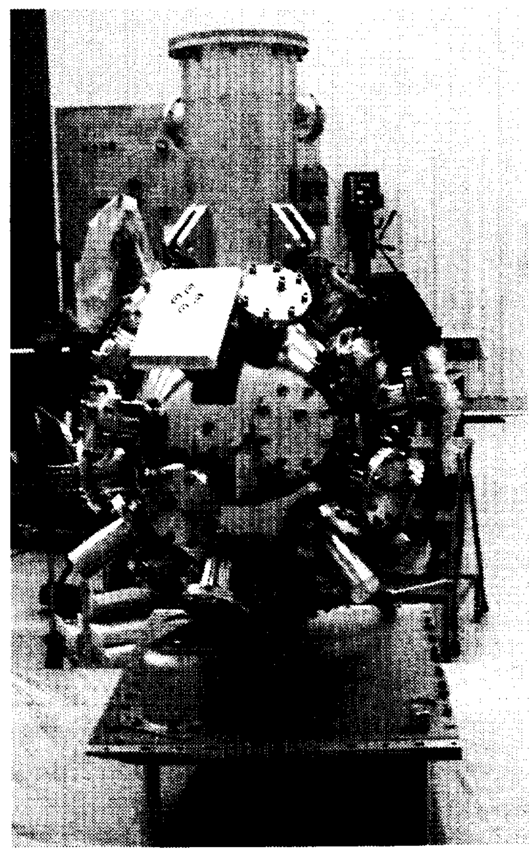
SB Apparatus

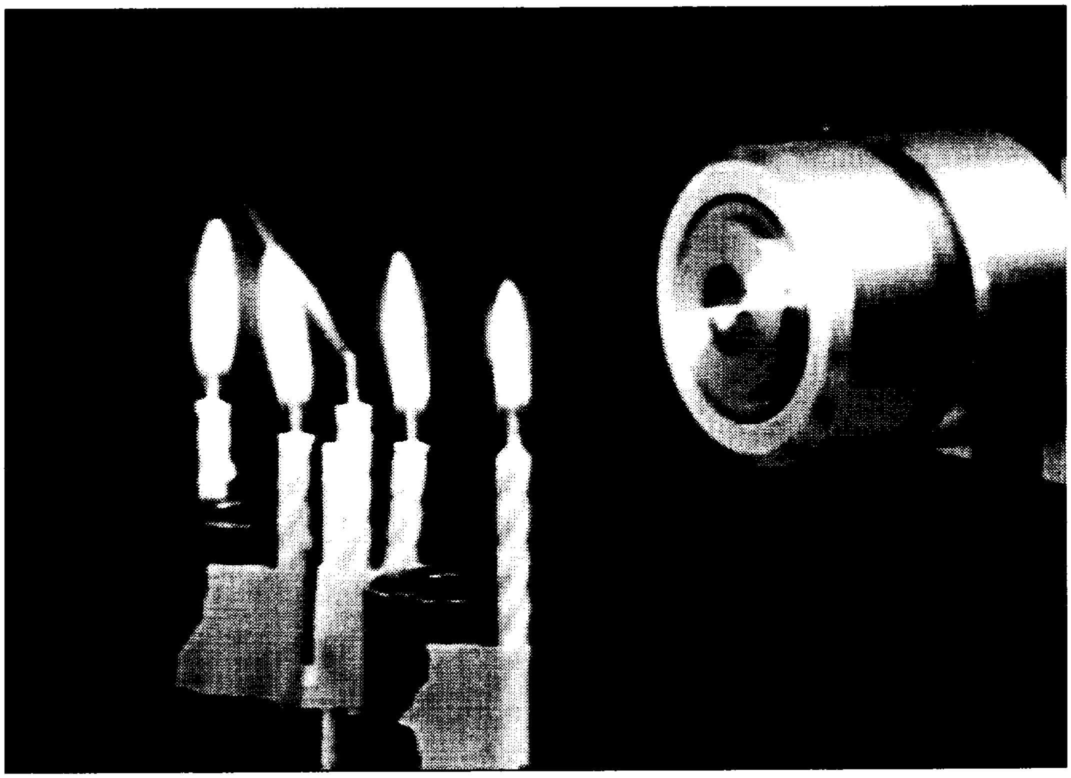
GUIGNÉ

Space-DRUMS®
Processing Chamber and Material Handling System

ISS Configuration for inside Processing Module

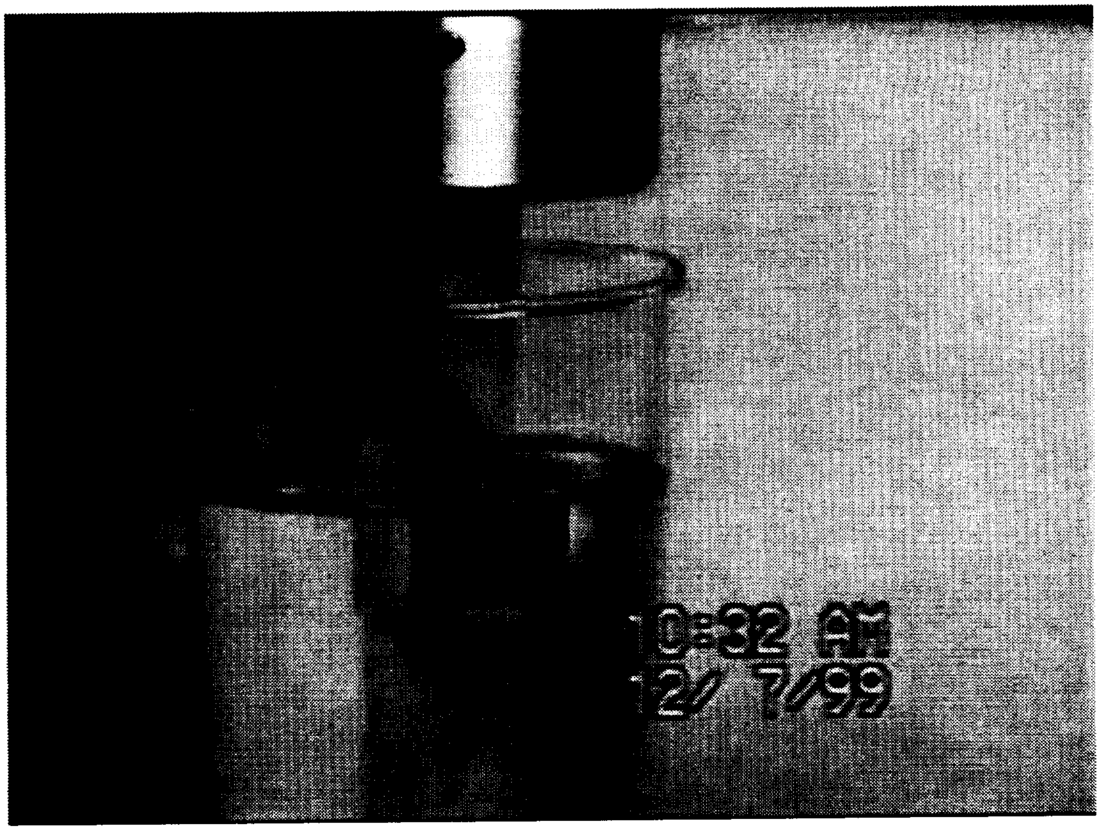
Launch ULF1





Candles.avi

OrbSphereNBigDrops.avi



ProjDrivWater.avi